Environmental life cycle assessment of seawater reverse osmosis desalination plant powered by renewable energy

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Abstract

This paper evaluates life cycle Greenhouse Gas (GHG) emissions of a Seawater Reverse Osmosis (SWRO) desalination plant and assesses its performance under three power supply scenarios. A Life Cycle Assessment (LCA) analysis is conducted for a plant located in Perth, Western Australia (WA). Input and output flows of SWRO plant are based on literature and Perth desalination plants. The Simapro Australian and Ecoinvent databases are used for operational phase Life Cycle Inventory (LCI). An LCI for the construction phase of the plant is developed using economic input–output analysis. Electricity supply scenarios are "100% WA grid", "100% wind energy" and "92% wind energy plus 8% Photovoltaic (PV) solar energy". Results indicate that renewable energy powered desalination plants achieve GHG emissions reduction of ~90% compared to the plant powered by WA grid scenario. For the plant powered by fossil based grid electricity, electricity use in the operational phase is found to be responsible for more than 92% of its GHG emissions. On the other hand, for the plants powered by renewable energy, the highest contribution belongs to chemical use in the operational phase (60%) followed by the construction phase (17%). Indirect emissions due to the electricity consumption in the chemical, wind turbine and PV solar panel manufacturing are found to contribute the lion's share (36–39%) of the life cycle emissions for the renewable energy powered desalination plants. Any improvement in fuel mixes in grid electricity towards cleaner energy sources can be beneficial by reducing impacts associated with upstream electricity use in manufacturing. This work provides the first reference to identify and quantify supply chain contributions to the overall environmental impact associated with renewable energy powered desalination plants.

Keywords: Reverse osmosis; Desalination; Renewable energy; Life cycle assessment; Greenhouse gas emission

1 Introduction

The recent combination of climate change related rainfall reduction and rapid population growth in southwest Western Australia (WA) has posed great challenges for the balancing of water supply and water demand in that region. The state's Water Corporation forecasts water shortfalls for Perth and surrounding areas of around 331 GL annually by 2030 [1]. Water use restrictions, increased water recycling and development of new water sources are identified as strategies for securing reliable water supply in a drying climate. The most significant supply-side proposal involves the construction of Seawater Reverse Osmosis (SWRO) desalination plants on the northern and southern seaboard of the Perth metropolitan area. This technology could contribute nearly 50%~~ per cent~~ of new water source development by 2030 [1]. Moreover, half of the water supply for the area is currently sourced from two large SWRO plants [2]. To increase sustainability of this climate resilient water source, desalination plants in Perth are "paired" with wind and solar farms (Table 1). Water Corporation purchases the desalination plants electricity demand from three wind and solar farms annually and consumes the equivalent amount of electricity from WA grid electricity [2,3].

Table 1 Desalination plants and their energy sources in Perth.

Name	Plants capacity	Paired renewable source
Perth Seawater Desalination Plant	45 GL/year	Emu Downs Wind Farm [3]

Southern Seawater Desalination Plant (SSDP)	50 GL/year first phase and 50 GL/year second phase	Greenough River Solar Farm and Mumbida Wind Farm [2]

~~Note:~~ If two phases of the SSDP plant run at full capacity, the claimed renewable sources could not meet the energy demand of the plant. Second phase electricity supply strategy for SSDP is under review.

Powering desalination plants with renewable energy instead of the fossil based grid electricity reduces the desalination plants Greenhouse Gas (GHG) emissions. Comparing GHG emissions of the desalination plants powered by renewable energy with centralised water supply systems that use mixes of water sources including desalination, shows that the desalination alone is much more GHG intensive. The objective of this study is to identify and demonstrate the main sources of GHG emissions within the life cycle of desalination plants powered by renewable energy and compare their performance with those powered by fossil based grid electricity. Identification and quantification of supply chain contributions to the overall environmental impact associated with renewable energy powered SWRO are prerequisites in the development of strategies to reduce such impacts. Yet, the authors are unaware of any previous Life Cycle Assessment (LCA) studies of renewable energy powered SWRO plants that have provided contribution analysis. Through environmental impact assessment of the system, possibilities for further reducing the GHG emissions of plants powered by renewable energy source are identified.

The paper begins with brief review of the existing literature on the LCA of SWRO before presenting the LCA methodology and system boundary used.

2 Literature review

Although seawater desalination is one of the most climate resilient water sources, there are concerns over its potentially high environmental impact. Life cycle assessment (LCA) provides a comprehensive, ISO standardised method for evaluating such impacts [4]. Recently, LCA has been applied to investigate the environmental impacts of SWRO plants, mostly for the comparison of SWRO with other water sources and technologies [4–12]. Several of these studies identified the significant role of electricity consumption in the total life cycle environmental impact of SWRO powered by fossil based grid electricity. Raluy et al. [6] and Stokes et al. [9] found that the overall environmental impact of SWRO plants is significantly affected by their electricity supply fuel mix. Raluy et al. [6] compared Spanish, French, Norwegian and Portuguese models of electricity production on the life cycle airborne emissions associated with desalination technologies and concluded that the renewable energy based Norwegian grid produced the lowest emissions of the four by a substantial margin. Stokes et al. [9] compared six different electricity mixes – “California's average electricity mix”, the “US national mix”, “Solar PV”, “Solar thermal”, a “European Union 2020 mix” and a “hypothetical low emission mix” – for desalination, importation and recycling based water sources. They found that electricity production models with a higher share of renewable energy decreased the environmental impact of all water source categories. Biswas [10] accounted for the operational phase greenhouse gas (GHG) emissions of an SWRO desalination plant in Perth, WA using LCA method and proposed wind power as a GHG reduction strategy. GHG emission values associated with SWRO supply options in previous studies are summarised in Table 2. Although GHG emissions of SWRO powered with renewable energy have been accounted [9,10], no identification and quantification of supply chain contributions to the overall GHG emissions associated with renewable energy powered SWRO has been made. This information can be used to discover possible decisions to improve the supply chain of SWRO desalination plants powered by renewable energy. Another novelty of this study lies in the use of an economic input–output LCI method for accounting GHG emissions of construction phase of the desalination plant.

Table 2 GHG emissions associated with SWRO in the previous studies.

Electricity production model	System boundary	Electricity use (kWh/m^3)	kg CO_2 eq. emissions per m^3	Reference
Union for co-ordination of transmission energy electricity mix	Operational phase	2.50	1.40	Hancock et al., 2012 [12]
Singapore electricity mix	Construction and operational phase	3.90	2.20	Zhou et al., 2011 [11]
Western Australia electricity mix	Operational phase	–	3.80	Biswas, 2009 [10]
100% wind	Operational phase	–	0.32	Biswas, 2009 [10]
U.S. average mix	Construction and operational phase	5.10	3.95	Stokes et al., 2009 [9]
100% solar PV generation	Construction and operational phase	5.10	0.72	Stokes et al., 2009 [9]
100% solar thermal generation	Construction and operational phase	5.10	0.45	Stokes et al., 2009 [9]
European Union 2020 mix	Construction and operational phase	5.10	1.93	Stokes et al., 2009 [9]
Spain electricity mix	Construction and operational phase	–	1.9	Muñoz et al., 2008 [4]

3 Materials and methods

The method applied ISO14040 [13], with LCA conducted in four stages: goal and scope, inventory analysis, impact assessment, and interpretation. The sections that follow reflect this structure, with the first three stages described under headings of the same name.

3.1 Goal and scope

The first goal of this study is to provide life cycle GHG emissions quantification of an SWRO desalination plant powered by Scenario A "100% Western Australia grid", Scenario B "100% wind energy", and Scenario C "92% wind energy plus 8% solar PV". Scenarios B and C are electricity production models for powering SWRO desalination plants in Perth, WA (Table 2). The second goal is to identify and demonstrate the main sources of GHG emissions within the life cycle of the desalination plant. The functional unit for the study is one cubic metre~~er~~ of water, treated and distributed to a population centre. The scope of this study is primarily cradle to gate. More specifically, each Life Cycle Inventory (LCI) covers the construction phase and the operational phase for SWRO plants, with some coverage of the disposal phase for high impact inputs. The~~ main~~ input flows analysed ~~w~~were~~asere~~ chemical use, materials consumed for membrane replacement and electricity consumption associated with seawater extraction, water treatment and the distribution of desalinated water to final users. Disposed waste of membranes to landfill at the end of their assumed service life was also included in each LCI. Discharged streams to sewer due to 'clean in place' and chemically enhanced backwash, discharged brine to sea were also covered. The decommissioning of the system was not considered. The descriptions for the desalination plant and the energy sources are listed in Table 3.

Table 3 System assumptions and description.

	Assumptions	Descriptions
SWRO desalination plant		
Productivity	50 GL annually	Similar to SSDP.
Capacity factor	0.85	Adopted from Ref. [19].
Pre-treatment	Membrane pre-treatment	Similar to SSDP
Water distribution distance	75 km between plant and centre of demand area.	Similar to SSDP.
Distribution head loss	3 metre~~er~~ per kilometre	[20]
Treatment process electricity use	3.5 kWh/m^3	[21]
Membrane material	–	Adopted from Refs. [12,22]
Chemical use, waste disposal, material transportation	–	Adopted from Ref. [10] similar to SSDP
Infrastructure capital cost	0.19 ~~AU~~$AU/m^3	[19,23]
Plant life time	30 years	–
Wind farm		
Wind Turbine manufacturing	Manufactured in Europe	Adopted from Ref. [24]
Capacity factor	30%	Adopted from Ref. [24]
Life time	30 years	Adopted from Ref. [24]
Transmission network distance	400 km between the paired wind farm and the desalination plants	Similar to SSDP.
PV solar farm		
PV solar panel manufacturing	Manufactured in Europe	Adopted from Ref. [24]
Capacity factor	11%	Adopted from Ref. [24]
Life time	30 years	Adopted from Ref. [24]
Transmission network distance	400 km between the paired PV solar farm and the desalination plants	Similar to SSDP.

3.2 Life cycle inventory analysis method

A life cycle inventory (LCI) is the phase of LCA aimed at compiling all output emissions and wastes and also input resources as environmental flows [14]. In this study, LCI for construction phase was defined by economic input–output based (IO-based) LCI method. For operational phase, LCI was obtained by process based LCI method. Using economic input–output for construction phase was due to the process data limitation. The foreground data for the construction phase and operational phase are ~~in~~ in monetary and physical unit, respectively. Operational phase background data was obtained from available libraries in Simapro software [15]. Data were mostly selected from Australian database and the grid electricity and transportation were selected for WA. For material and processes, which were not available in Australian database, Ecoinvent library was used as a supplement database.

Construction phase background data were calculated by following Economic IO-based LCI model [16] and matrix calculations were conducted with Matlab software.

$$Q = N \cdot \boldsymbol{x}^{-1} \tag{1}$$

$$A = Z \cdot \boldsymbol{x}^{-1} \tag{2}$$

$$Q^{*} = Q(I - A)^{-1}, \tag{3}$$

where

$N = [n_{kj}]$ is a matrix of “Ecological Commodity Output”, n_{kj} indicates the amount of ecological commodity output k associated with the output of sector j in physical unit.

$x = [x_i]$ is a vector of “Total Output”, x_i indicates the total industry output summation of output consumed by intermediate industries, final users and exports, x is diagonal matrix with the elements of x strung out along its main diagonal.

$Z = [z_{ij}]$ is a matrix of “Interindustry Transactions”, Z_{ij} indicates the amount of output from industry sector i used by industry sector j in monetary unit.

$I = [i_{ij}]$ is an identity matrix.

$Q^{*} = [q_{ij}]$ is a matrix where q_{ij} reflects the amount of ecologic output i associated with delivering a dollar's worth of industry j output to final demand directly and indirectly.

The “Interindustry Transactions” and “Total Output” matrix were obtained from latest 2008–2009 industry by industry flow table published by Australian Bureau of Statistics [17]. There are 111 industry sectors, which make a Z matrix of 111 × 111. The sector of “Non-Residential Building Construction” (NS) was selected to represent construction of the water supply system. The primary data for “Ecological Commodity Output” matrix was obtained from “National Greenhouse Gas Inventory” [18] with database consisting of 12 pollutants to air. The emissions associated with delivering one 2009 $AU worth of NS industry sector were computed and exported to Simapro software as background data for construction phase.

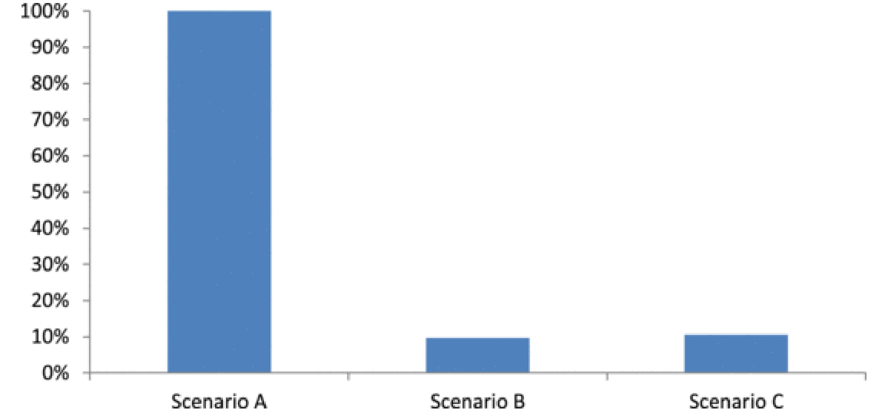
3.3 Life cycle impact assessment method

Life cycle impact assessment (LCIA) is the final phase of LCA in which inventory data are converted into impact results through the use of appropriate algorithms or indicators, to simplify understanding and assessing the environmental impact of a product system [14]. GHG emissions in ~~K~~kg CO_2 equivalent were~~as~~ calculated based on the International Governmental Panel on Climate Change (IPCC) 2007 method for the timeframe of 100 years with Simapro software [15].

4 Results and discussion

4.1 Baseline comparative LCIA of scenarios

The normalis~~z~~ed GHG emissions of the three scenarios are shown in Fig. 1. Scenarios B and C are normalis~~z~~ed by the maximum value observed in Scenario A. Results in Fig. 1 indicated that the desalination plants powered by renewable sources (Scenarios B & C) produced a similar degree of emissions, while the plant powered by fossil based grid electricity produced nearly 90% higher emissions. Moreover, the results showed that in Scenario C, replacing 8% of the wind energy with the PV solar in the energy scheme, increased the emissions by 1% compared to Scenario B.



Online view | Print view

Fig. 1 Relative impact of Scenarios A, B and C. The maximum values observed for GHG emissions for Scenarios A, B and C are 4.61, 0.446 and 0.491 kg CO_2 eq. per ~~/~~m^3 water produced, respectively.

It is worth noting that the emissions associated with the plant powered by WA grid in this study are higher than Biswas, 2009 study [10]. This is due to the fact that the system boundaries of the studies are different. Biswas, 2009 accounted GHG emissions associated with operational phase, while in this study construction phase and distribution pumping are~~is~~ also included. In addition, GHG emissions of the desalination plant in this study and Biswas [10] are higher than plants located in Singapore [11] and Europe [4,12], mostly due to the different grid fuel mixes. Western Australia, Singapore, and UCTE grid electricity fuel mixes consist of more than 90% (mostly hard coal and natural gas), 95% (mostly natural gas), 40% (mostly hard coal and natural gas) fossil fuel, respectively. Although there is some variance in the previous literature results, systems powered by renewable sources consistently appear as the lowest GHG producing options.

4.2 Contribution analysis

According to ISO14044 standard [13], identifying key materials and processes with the dominant environmental impacts during the life cycle of systems has a significant role in interpretation phase of LCA studies. This section provides detailed contribution analysis of the desalination plant GHG emissions for three electricity production scenarios (Fig. 2).

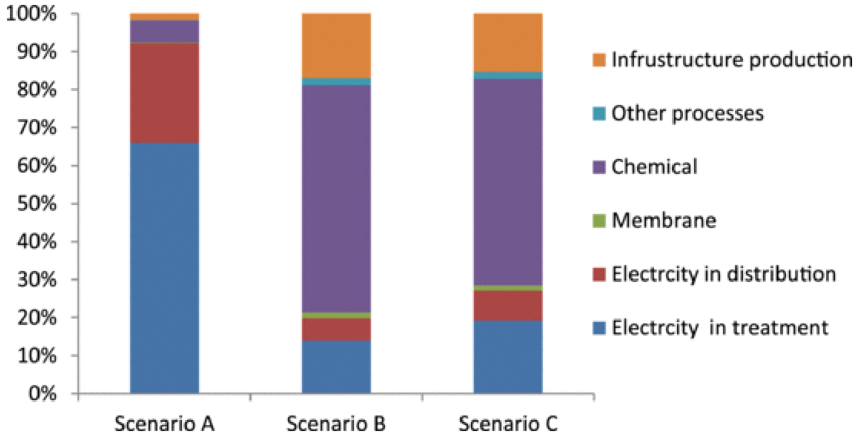


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Fig. 2 Contribution analysis of sub~~-~~systems to the life cycle GHG emissions for Scenarios A, B and C.

The electricity uses in the treatment and distribution processes for Scenario A is shown to be the dominant factor, which is responsible for more than 92% of the GHG emissions contribution. This is due to the electricity production model in Scenario A, which is mostly fossil fuel based. Further detailed contribution analysis was conducted to identify the key sub-processes for WA grid electricity. Results showed that the high contribution of the GHG emissions from WA grid electricity is associated with coal burning activities in power plants. For Scenario B, powered by wind source, electricity use is the second most significant contribution (20%). Within the electricity sourced by wind farm, wind plant moving parts, fixed part, electricity transmission facilities and gear oil have the contribution of 42%, 36%, 20%, and 2% respectively. High contribution of wind turbines production in the life cycle of the wind farm was also highlighted in previous LCA studies [25,26]. In Scenario C, the contribution of the electricity emissions in total life cycle increases by 27% compared with Scenario B. This is due to the fact that the PV solar farm emits higher GHG emissions per kWh electricity produced compared with wind farms electricity in this study. Detailed contribution analysis within the electricity sourced by PV solar farm system showed that solar modules, rolled steel and concrete facilities and transmission facilities have the contribution of 62%, 30%, 3% and 5% respectively.

In these three scenarios, the chemical use is responsible for emission of 0.267 kg CO_2 eq. per m^3 water produced. The chemical use accounts for 6% of GHG emissions in Scenario A. This is the second significant contribution after electricity use. For Scenarios B and C, powered by the renewable sources, chemical use is the major contributor, accounted for 60% and 54% of GHG emissions in the life cycle of the systems. Within the chemical use subsystem, transportation of the chemical from the chemical manufacturing plant to the desalination plant has less than 4% contribution while, nearly 48% of the GHG emission emits from the fossil based grid electricity used in the chemical manufacturing.

The infrastructure construction phase of the desalination plant emits 0.0754 kg CO_2 eq. per m^3 produced water in the three scenarios. The construction phase is accounted for 2% contribution of the total life cycle GHG emissions in Scenario A. This contribution increases to 17% in Scenario B and 15% in Scenario C, which makes their construction phase impacts the third significant contributors in their total life.

Two subsystems of membrane material consumption plus other processes (waste and wastewater management) contribute to less than 1% GHG in Scenario A, 4% in Scenario B and 3% in Scenario C.

Generally, in Scenarios B and C, the chemical consumption is the sub-process with the highest GHG emissions while in Scenario A the highest contribution belongs to electricity consumption in the treatment and distribution processes. Results highlighted consequences of high chemical use in SWRO desalination plants regarding their life cycle GHG emissions. While the previous studies mainly emphasised on the importance of electricity use in GHG emissions of desalination plants, these findings showed the importance of chemical use in desalination plants powered by renewable sources. This means that optimis~~z~~ation of the SWRO treatment process to either reduce the amount of chemical use or consume more environment friendly chemicals can further improve the environmental performance of desalination plants.

4.3 Upstream electricity in manufacturing

More detailed analyses were conducted to further identify the role of material manufacturing electricity use in GHG emissions of the desalination plants powered by renewable energy (Table 4). The results indicated the significant contribution of upstream electricity use in the desalination plant life cycle GHG emissions (36.1% in Scenario B & 39.8% in Scenario C). The contribution of the electricity in chemical manufacturing is shown to be the dominant factor for both scenarios. For Scenario B powered by wind energy, electricity required for the wind turbine manufacture is the second most significant contribution. When the PV solar sources included in the energy production model in Scenario C, the upstream electricity use in the PV solar manufacture becomes the second greatest contribution and the wind turbine manufacture moves to the third. This is due to the fact that PV solar module manufacture is more electricity intensive in compared to wind turbine manufacture. In both scenarios, contribution of membrane modules manufacturing is insignificant.

Table 4 The electricity use and the GHG emissions contribution of the material manufacturing under 30 years water supply system life time.

Scenario		Wind farm material	PV solar farm material	Chemical	Membrane modules
B	Electricity use (~~K~~kWh/m^3 water produced)	0.017	–	0.154	0.001
	Contribution in total life GHG emissions	2.8%	–	33.5%	0.2%
C	Electricity use (~~K~~kWh/m^3 water produced)	0.016	0.014	0.154	0.001
	Contribution in total life GHG emissions	2.1%	7.4%	30.2%	0.1%

Results highlight high contribution of material manufacture electricity use in GHG emissions of SWRO desalination plants powered by renewable sources. This means that life cycle GHG emissions of SWRO desalination plants are highly influenced by GHG emissions of electricity use in material manufacturing. Any improvement in electricity production scheme for material manufacturers toward cleaner energy sources can be beneficial.

4.4 Sensitivity analysis

A sensitivity analysis was carried out to find out to what extent the life cycle GHG emissions of the desalination plant is influenced by site-specific factors (water distribution, electricity transmission and material transportation distance) and also the process specific factors (electricity and chemical use in treatment process) in the three scenarios (Table 5). The sensitivity was calculated based on deviation of ±50% even though for process specific factors this may not be realistic. The analysis showed that the GHG emissions of the desalination plant powered by fuel based electricity are more sensitive to the electricity use, while GHG emissions of the renewable sourced plants are more sensitive to the chemical use. This is consistent with the previous discussion (Section 4.2) on the differences between contribution analysis results of the plant powered by fossil based grid electricity and the plants powered by renewable sources. Additionally, Scenario C is more sensitive to the electricity use than Scenario B. This is due to the fact that the 8% PV solar source in Scenario C produces more GHG than the same amount of wind source in Scenario B.

Table 5 GHG emissions sensitivities based on deviation of ±50% for variables.

Scenario	Water distribution distance	Electricity transmission distance	Material transportation distance	Electricity use in treatment process	Chemical use in treatment process
A	±13.23%	–	±0.22%	±32.97%	±3.04%
B	±3.00%	±1.66%	±0.76%	±7.26%	±30.78%
C	±4.15%	±1.51%	±0.96%	±9.85%	±27.96

Amongst the site-specific factors, results are more sensitive to the water distribution distance. The GHG emissions are however less sensitive to change of the electricity transmission distance and material transportation. This is because these two subsystems produce a small portion of the total GHG emissions. Electricity for water pumping emits water distribution process emissions. Electricity transmission system emissions are due to the transmission network infrastructure. Generally, any location optimis~~z~~ation in order to reduce water distribution and electricity transmission emissions can be beneficial.

5 Conclusion

The results of this study are in agreement with the previous studies that GHG emissions of seawater desalination plants decrease by powering the plants with renewable energy instead of fossil based electricity. Uniquely, identification and quantification of supply chain contributions to the overall GHG emissions associated with renewable energy powered SWRO were~~as~~ conducted in this study using LCA method. Results indicated that GHG emissions of plants powered by renewable sources are highly dependent on chemical use in treatment process. The second most significant GHG emission contributors are wind and PV solar farm sub~~-~~systems. Moreover, detailed contribution analysis discovered that indirect emissions due to the electricity consumption in chemicals, PV solar panels and wind turbines manufacturing stage are found to contribute to the lion's share of the life cycle emissions for the renewable energy powered desalination plants. However, one should consider the dependency of this finding on the geographical location of the material manufacturer that effects the GHG emissions of the upstream electricity used in the manufacturing. Finally, minimis~~z~~ing water distribution and electricity transmission distance will reduce the GHG emissions of the system.

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Highlights

- Life cycle assessment of a reverse osmosis desalination plant was conducted.
- GHG emissions could be reduced through the use of renewable energy as a power source.
- Chemical use reduction is a potential strategy to reduce plant emissions.
- Electricity use in ~~wind turbine~~ materials manufacturing has high contribution in emissions.

Queries and Answers

Query: Please check the journal title and page range in Ref. [10] and correct if necessary.

Answer: Journal is World Academy of Science,Engineering and Technology 56 2009 and there is not any abbreviation for it.

Page range is correct.

Query: Please confirm that given names and surnames have been identified correctly.

Answer: I would like to confirm that names are correct.